Ground-based Light Curve Follow-up Validation Observations of TESS Object of Interest (TOI) 5868.01

Lucas Chiang[1] and Peter Plavchan[2]

[1]Department of Physics and Astronomy, George Mason University, Fairfax, VA 22030, USA
[2]Department of Physics and Astronomy, George Mason University, Fairfax, VA 22030, USA

ABSTRACT

Context. Observing and analyzing transiting planets around host stars is crucial to our understanding of the formation and evolution of planetary systems. Through the Transiting Exoplanet Survey Satellite (TESS) mission, TESS Object of Interest (TOI) 5868.01 was identified as a possible exoplanet around host star TOI 5868.

Aims. The focus of this paper is validating the predicted transit that may lead to the identification of TOI 5868.01. We compared ground-based data with predicted data from the TESS mission to confirm that TOI 5868.01 is an exoplanet.

Methods. We created TESS light curves using Python's Jupyter Notebook. We then plate-solved images taken at the George Mason University Observatory from June 6, 2024 to June 7, 2024 to conduct multi-aperture photometry through AstroImageJ (AIJ). Using the data collected, we created a ground-based light curve and Near Eclipsing Binary (NEB) analysis.

Results. We concluded that the chance of TOI 5868.01 being an exoplanet is high, as the processed data was similar to the predicted data and was statistically significant. However, more future work is needed to validate that TOI 5868.01 is an exoplanet as we were not able to completely rule out the possibility of a false positive.

1. Introduction

This paper is a follow up of an identified object of interest from the Transiting Exoplanet Survey Satellite (TESS) Mission. The TESS Mission identifies possible exoplanet candidates to be further researched and validated to be an exoplanet by multiple ground-based observations and analyses. Currently, there are more than 4,000 TESS Objects of Interest (TOIs) that require validation. This paper builds on many previous publications on this subject of study to advance our knowledge of exoplanets. For example, a publication entitled "Ground-Based Light Curve Follow-Up Validation Observations of TESS Object of Interest 5691.01" (Adam Tong, Aiden Kriel, and Peter Plavchan) used a ground-based analysis with AstroImageJ (AIJ) to validate TOI 5691.01. In this paper, we present follow-up observations of TOI 5868.01. TOI 5868.01 is a less observed TOI and therefore there will be a need for continued ground-based observation, even if the observations that we made provide conclusive results. Its orbital period is 2.68 days and its radius is 14 times the radius of the Earth. It orbits a star 2.41 times the radius of our sun with an effective temperature of 6,875.8 Kelvin. The goal of our investigation is to determine whether or not the transit occurs on the expected star at the predicted time, with the expected duration and depth. In Section 2, we present our observations from TESS and the George Mason University 0.8m telescope. In Section 3, we present our analysis of the TESS light curve for TOI 5868.01 and our ground-based light curve analysis. In Section 4, we present our light curve results. In Section 5, we discuss our results, and in Section 6, we present our conclusions and future work.

2. Observations

In Section 2.1, we present the TESS Object of Interest 5868.01 and its exoplanet candidate properties, as well as its host star properties from the TESS Input Catalog, the Gaia mission, and other archival sources. In Section 2.2, we present the TESS sector light curve(s). In Section 2.3, we present a summary of the observational data collected with the George Mason University 0.8m telescope.

2.1. Exoplanet Candidate Properties

According to the TESS Input Catalog website, TOI 5868.01 or TIC 236158940 exhibits an effective temperature of 6,876 ± 104.841 K. Located 756.82 ± 18.52 parsecs away from Earth, TOI 5868.01 has a right ascension of 20:53:40.689, a declination of +34:21:05.93, a transit midpoint of 10486.6809 BJD_{TDB}, a transit duration of 2 hours and 53 minutes ± 17 minutes, and a transit depth of 3.310 part per trillion (ppt). TOI 5868.01's radius is 14 times the Earth's radius and its stellar radius is 2.41 times the size of our Sun (*TESS Project Candidates*, n.d.)

2.2: TESS Light Curves

Using Python's Jupyter Notebook, we used the Mikulski Archive for Space Telescopes (MAST) archive data from TESS to reproduce the light curve provided by TESS and replicate a transit. The red line on the graph in Figure 2.1 represents the transit replicated from the MAST data.

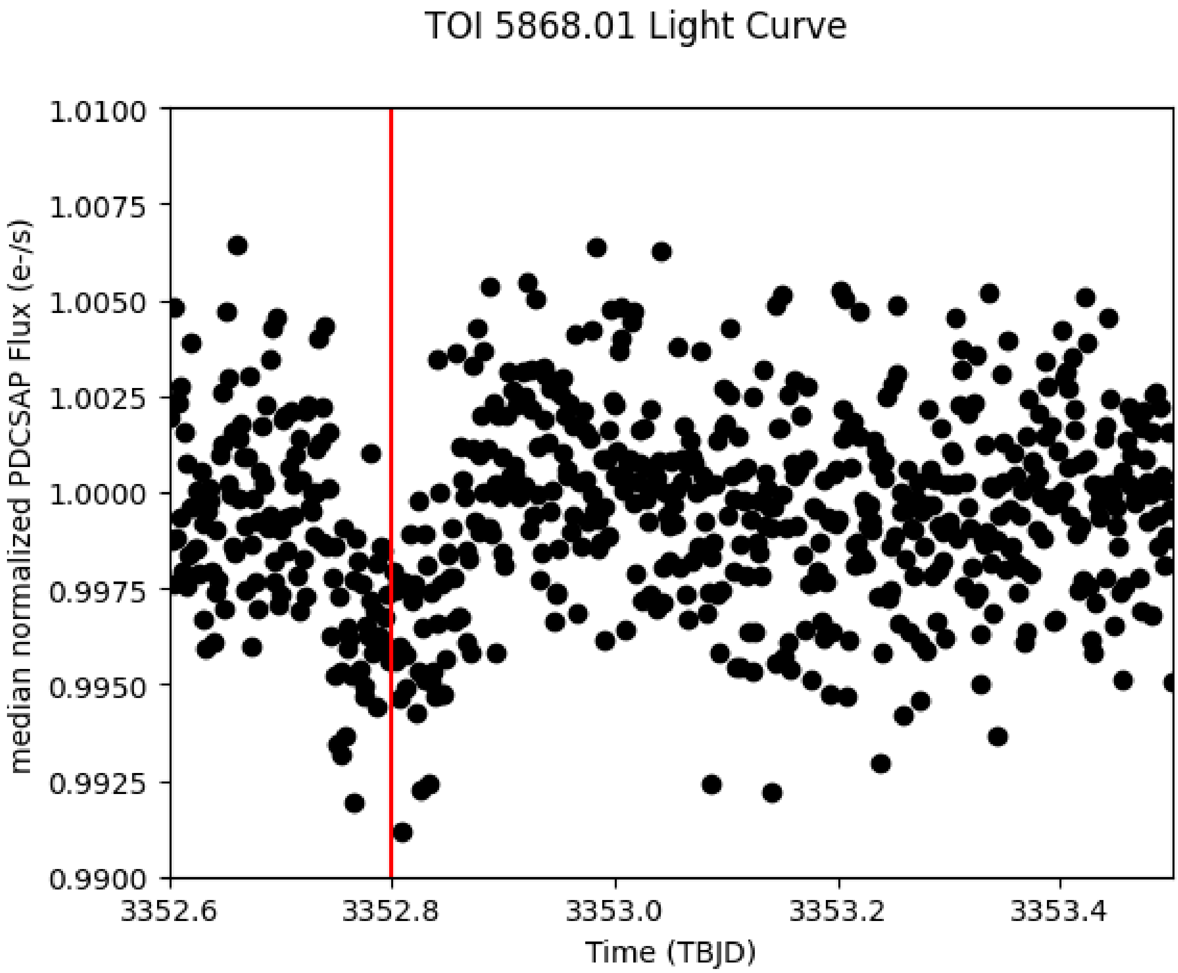


Figure 2.1: Python-Generated Light Curve

2.3: Ground Observations

We observed TOI-5868.01 overnight on June 6, 2024 using the George Mason University 0.8m telescope with an R filter. A total of 280 science photos were taken, with an exposure time of 65 seconds starting at 9:50 p.m. Eastern Standard Time (EST) and ending at 4:30 a.m. EST. The ingress time started at 11:39 p.m. EST on June 6, 2024 and ended at 1:02 a.m. EST on June 7, 2024. Thus, the observed duration of the transit was 1 hour and 23 minutes.

3. Analysis

In Section 3.1, we present the tools we used to analyze the TESS sector light curves. In Section 3.2, we present our analysis of the ground-based light curve using AIJ.

3.1 TESS Light Curve Analysis

In Figure 2.1, the TESS light curve shows a slight variation in flux, indicating a transit. We took our initial light curve data from the MAST Archive and used matplotlib, astropy.io, and numpy to analyze and graph the data. We used a large field of view (FOV) to find where the light curve was, as shown in Figure 3.1. We then adjusted the settings to identify the transit on the light curve, as shown in Figure 3.2, placed a red line on the transit, and zoomed in to obtain the TESS light curve shown in Figure 2.1.

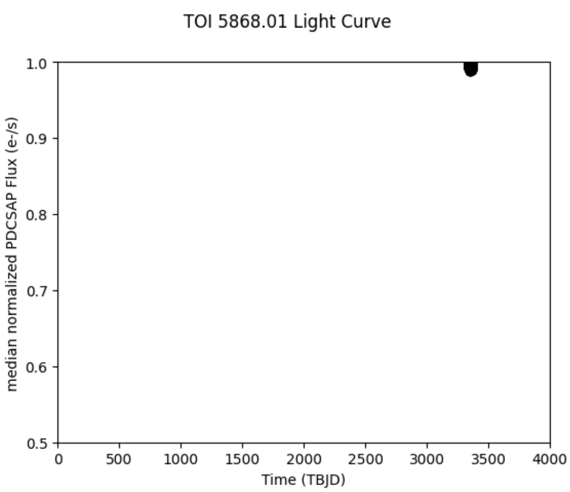


Figure 3.1: Large FOV used to find light curve data

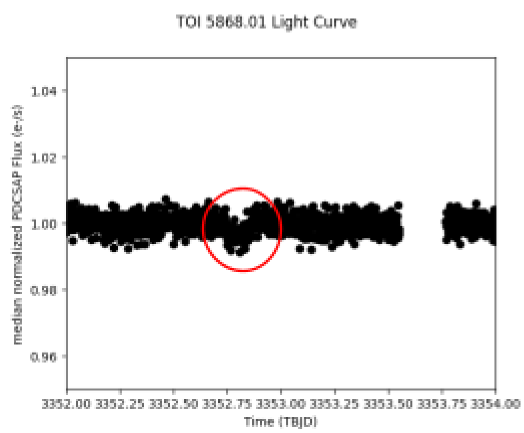


Figure 3.2: Identifiable transit on light curve

3.2 Ground-Based Analysis using AstroImageJ

Reduction/Plate Solving

All our analysis followed the steps discussed in the "Campus Telescope TESS Follow-Up Light Curve Tutorial" (Plavchan et al. 2022). Each science image produced was first visually inspected to look for any streaking or instrumental errors. Problematic sciences were thrown out and not analyzed by AIJ. We processed the images by subtracting the dark images and dividing them by flats. We then used AIJ's automatic plate solving using the ansvr local server to run astrometry.net and identify the astronomical objects in the image. After plate solving, AIJ assigned right ascension (RA) and declination (DEC) coordinates to the image.

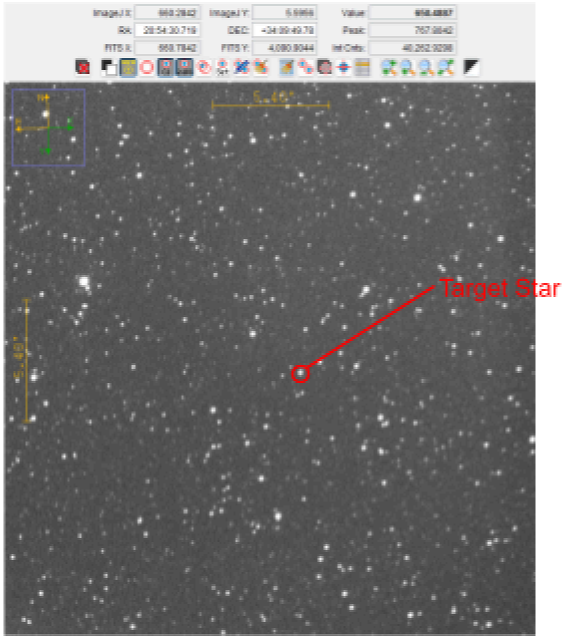


Figure 3.3: A plate-solved image with the target star in acceptable view.

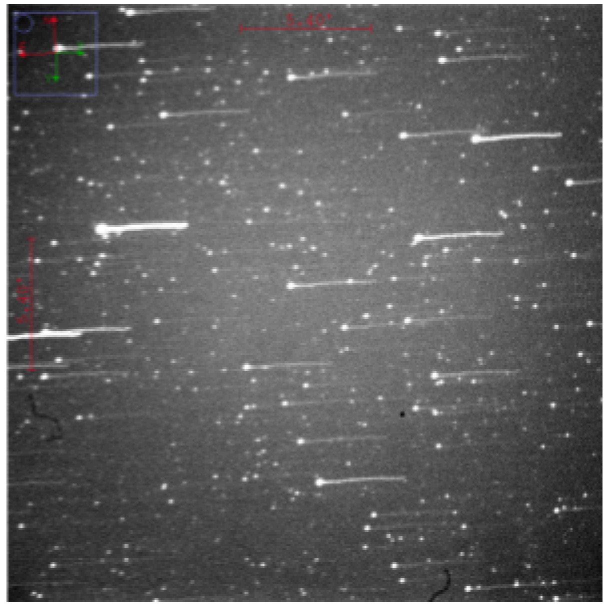


Figure 3.4: An image that had obvious streaking and had to be cut.

Light Curve Extraction

AIJ created a light curve from aperture photometry. The target star was selected from a plate-solved image and created a seeing profile (see Figure 3.5) that gave the value of the radius, inner annulus, and outer annulus to be used during multi-aperture photometry. We inputted the location of the George Mason University Observatory and a set of Gaia stars that are reference stars checking for a Near Eclipsing Binary (NEB). We then proceeded with multi-aperture photometry and created 15 different comparison stars that were later used in the light curve. After this process, we created a measurements table (see Figure 3.6) that was used to create our light curve.

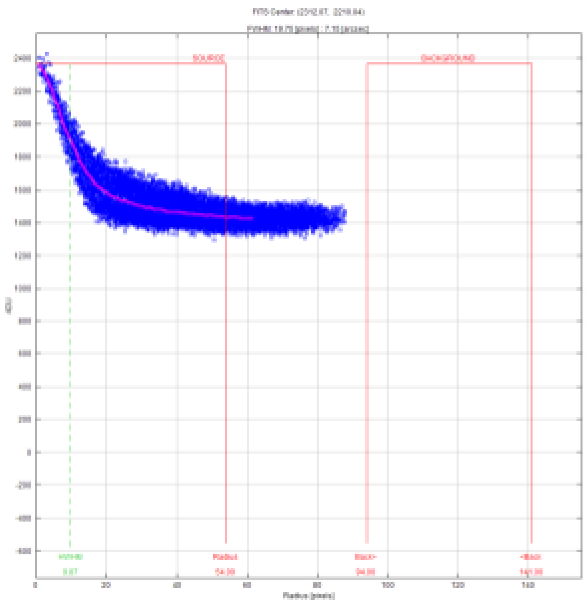
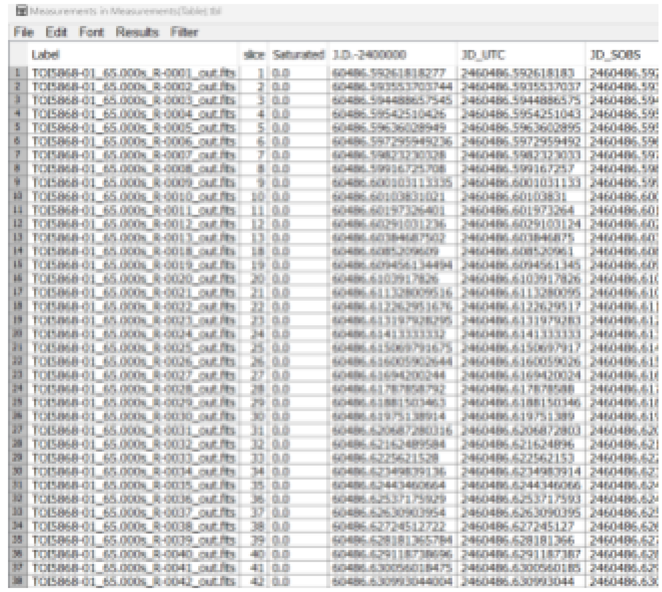


Figure 3.5: Seeing profile generated by AIJ



	Label	slice	Saturated	J.D.-2400000	JD_UTC	JD_SOBS
1	TOI5868-01_65.000s_R-0001_out.fits	1	0.0	60486.59261818277	2460486.592618183	2460486.592
2	TOI5868-01_65.000s_R-0002_out.fits	2	0.0	60486.593553703744	2460486.5935537037	2460486.593
3	TOI5868-01_65.000s_R-0003_out.fits	3	0.0	60486.594488657545	2460486.5944886575	2460486.594
4	TOI5868-01_65.000s_R-0004_out.fits	4	0.0	60486.59542510426	2460486.5954251043	2460486.595
5	TOI5868-01_65.000s_R-0005_out.fits	5	0.0	60486.59636028949	2460486.5963602895	2460486.595
6	TOI5868-01_65.000s_R-0006_out.fits	6	0.0	60486.597295949236	2460486.5972959492	2460486.596
7	TOI5868-01_65.000s_R-0007_out.fits	7	0.0	60486.59823230328	2460486.5982323033	2460486.597
8	TOI5868-01_65.000s_R-0008_out.fits	8	0.0	60486.59916725708	2460486.599167257	2460486.598
9	TOI5868-01_65.000s_R-0009_out.fits	9	0.0	60486.600103113335	2460486.6001031133	2460486.599
10	TOI5868-01_65.000s_R-0010_out.fits	10	0.0	60486.60103831021	2460486.60103831	2460486.600
11	TOI5868-01_65.000s_R-0011_out.fits	11	0.0	60486.60197326401	2460486.601973264	2460486.601
12	TOI5868-01_65.000s_R-0012_out.fits	12	0.0	60486.60291031236	2460486.6029103124	2460486.602
13	TOI5868-01_65.000s_R-0013_out.fits	13	0.0	60486.60384687502	2460486.603846875	2460486.603
14	TOI5868-01_65.000s_R-0018_out.fits	18	0.0	60486.6085209609	2460486.608520961	2460486.608
15	TOI5868-01_65.000s_R-0019_out.fits	19	0.0	60486.609456134494	2460486.6094561345	2460486.609
16	TOI5868-01_65.000s_R-0020_out.fits	20	0.0	60486.6103917826	2460486.6103917826	2460486.610
17	TOI5868-01_65.000s_R-0021_out.fits	21	0.0	60486.611328009516	2460486.6113280095	2460486.610
18	TOI5868-01_65.000s_R-0022_out.fits	22	0.0	60486.612262951676	2460486.6122629517	2460486.611
19	TOI5868-01_65.000s_R-0023_out.fits	23	0.0	60486.613197928295	2460486.6131979283	2460486.612
20	TOI5868-01_65.000s_R-0024_out.fits	24	0.0	60486.61413333332	2460486.614133333	2460486.613
21	TOI5868-01_65.000s_R-0025_out.fits	25	0.0	60486.615069791675	2460486.6150697917	2460486.614
22	TOI5868-01_65.000s_R-0026_out.fits	26	0.0	60486.616005902644	2460486.6160059026	2460486.615
23	TOI5868-01_65.000s_R-0027_out.fits	27	0.0	60486.61694200244	2460486.6169420024	2460486.616
24	TOI5868-01_65.000s_R-0028_out.fits	28	0.0	60486.61787858792	2460486.617878588	2460486.617
25	TOI5868-01_65.000s_R-0029_out.fits	29	0.0	60486.61881503463	2460486.6188150346	2460486.618
26	TOI5868-01_65.000s_R-0030_out.fits	30	0.0	60486.61975138914	2460486.619751389	2460486.619
27	TOI5868-01_65.000s_R-0031_out.fits	31	0.0	60486.620687280316	2460486.6206872803	2460486.620
28	TOI5868-01_65.000s_R-0032_out.fits	32	0.0	60486.62162489584	2460486.621624896	2460486.621
29	TOI5868-01_65.000s_R-0033_out.fits	33	0.0	60486.6225621528	2460486.622562153	2460486.622
30	TOI5868-01_65.000s_R-0034_out.fits	34	0.0	60486.62349839136	2460486.6234983914	2460486.623
31	TOI5868-01_65.000s_R-0035_out.fits	35	0.0	60486.62443460664	2460486.6244346066	2460486.624
32	TOI5868-01_65.000s_R-0036_out.fits	36	0.0	60486.62537175929	2460486.6253717593	2460486.624
33	TOI5868-01_65.000s_R-0037_out.fits	37	0.0	60486.62630903954	2460486.6263090395	2460486.625
34	TOI5868-01_65.000s_R-0038_out.fits	38	0.0	60486.62724512722	2460486.627245127	2460486.626
35	TOI5868-01_65.000s_R-0039_out.fits	39	0.0	60486.628181365784	2460486.628181366	2460486.627
36	TOI5868-01_65.000s_R-0040_out.fits	40	0.0	60486.629118738696	2460486.6291187387	2460486.628
37	TOI5868-01_65.000s_R-0041_out.fits	41	0.0	60486.630056018475	2460486.6300560185	2460486.629
38	TOI5868-01_65.000s_R-0042_out.fits	42	0.0	60486.630993044004	2460486.630993044	2460486.630

Figure 3.6: The measurement table generated by multi-aperture photometry

Finally, we changed the light curve until we could see all the data and altered the formation of the apertures to our preference. We created an NEB Check to scan for any Near-Eclipsing Binaries.

4. Results

In Section 4, we present the results of our ground-based light curve in Figure 4.1, our NEB Check (Dmag vs. RMS plot) in Figure 4.2, and the overlay of the normalized relative flux depth over time for the target star in Figure 4.3.

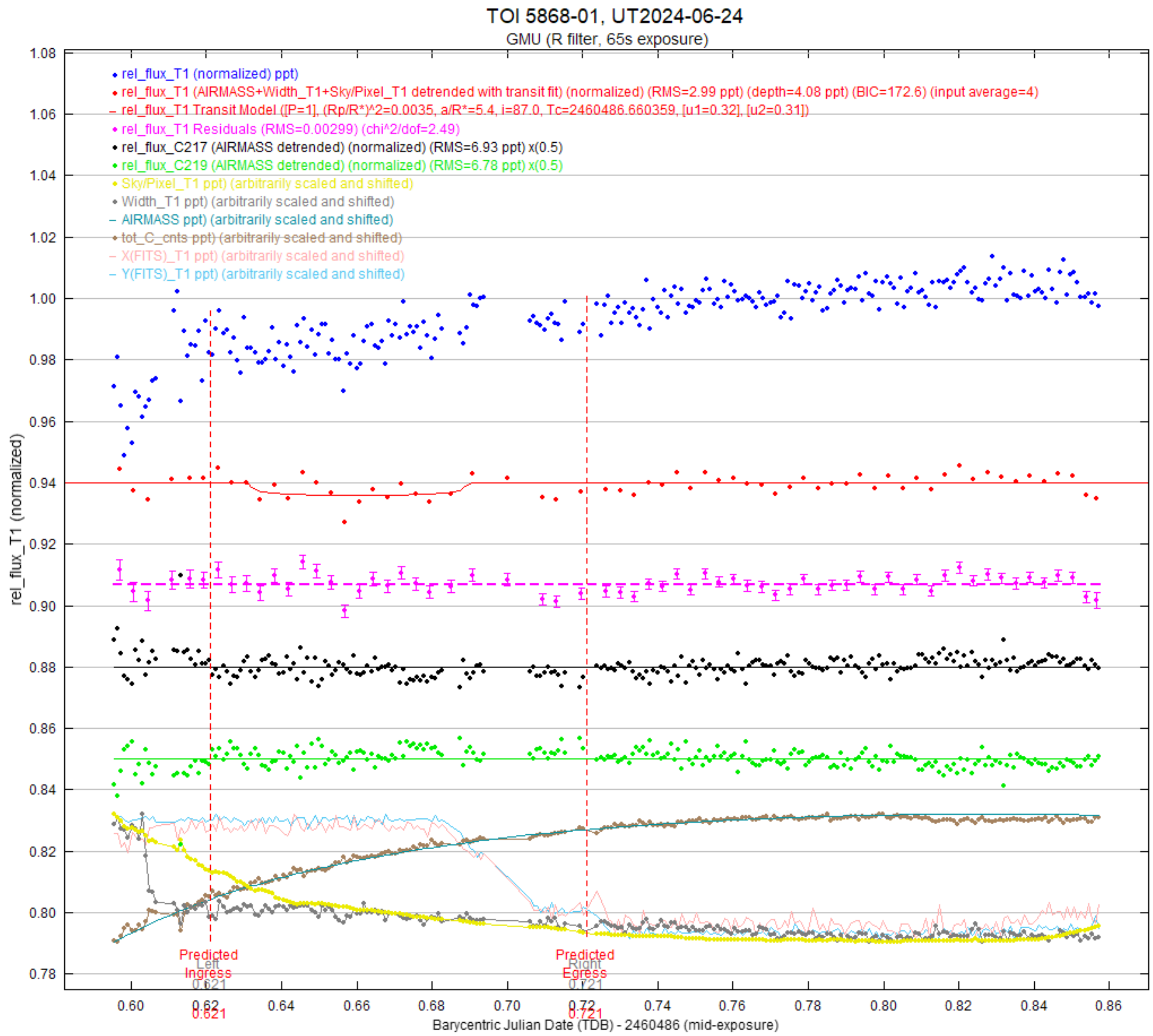


Figure 4.1: Ground-based light curve

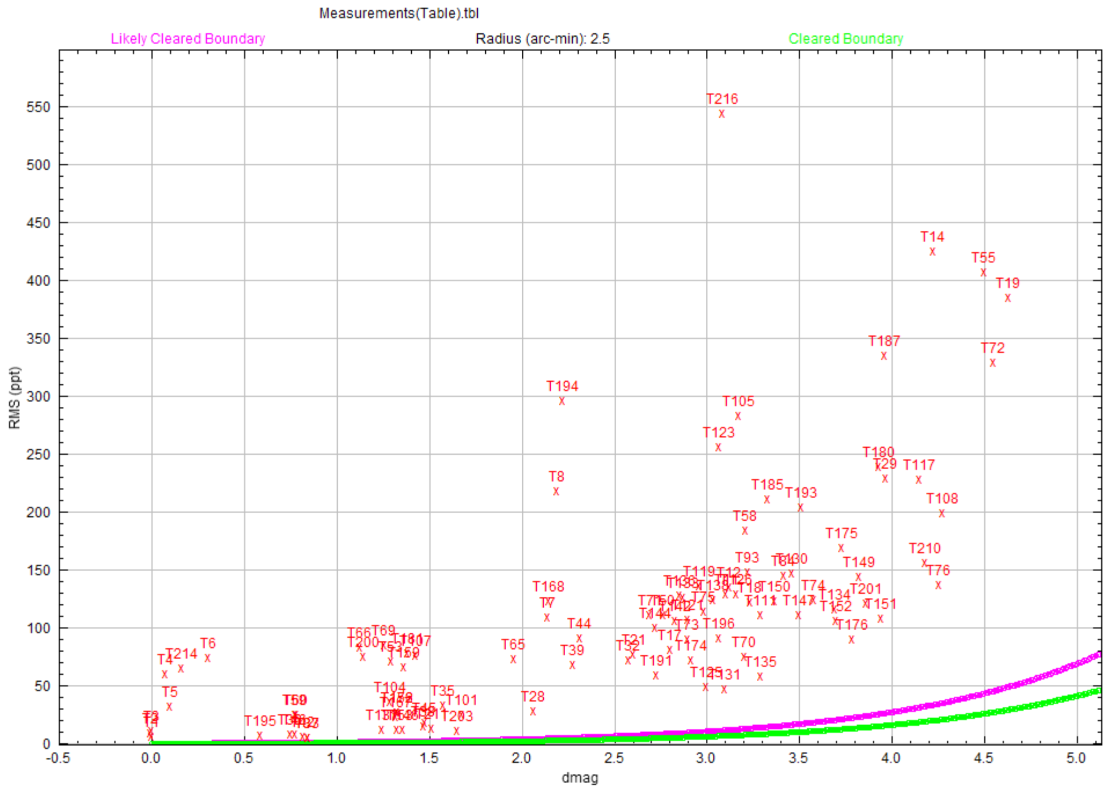


Figure 4.2: NEB Check (Dmag vs RMS plot)

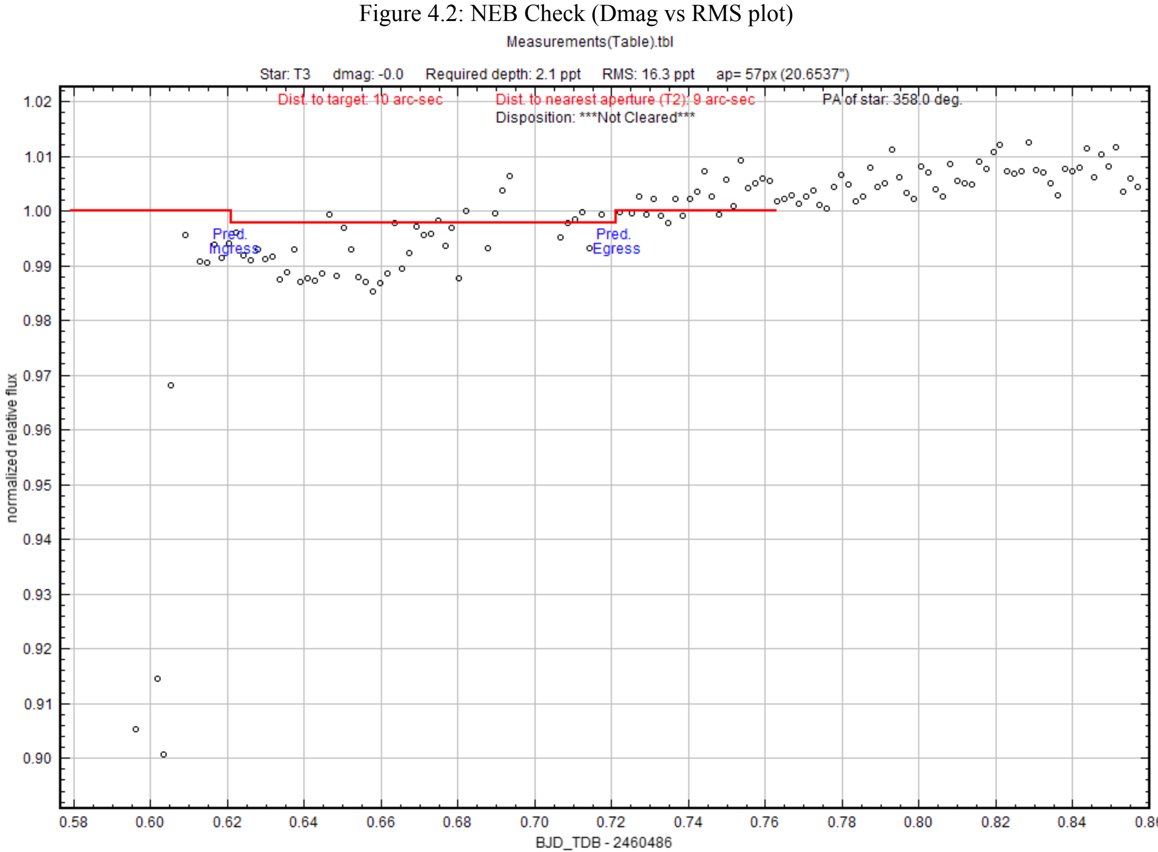


Figure 4.3: Normalized Relative Flux Depth over Time (BJD_TDB) for Target Star

5. Discussion

In Section 5.1, we share the interpretation of our results. In Section 5.2, we discuss our results in the context of the greater field of follow-up exoplanet validations from the NASA TESS mission.

5.1 Interpretation of the Results

Our results showed that TOI 5868.01 is most likely an exoplanet. The TESS light curve displayed a very noticeable pattern of transit. The predicted depth was very similar to the observed depth, with an observed depth of 4.08 ppt and a predicted depth of 3.31 ppt. Our scatter was also relatively low, with an RMS of 2.99 ppt, and our observed ingress and egress times were close to our predicted ingress and egress times. Although the NEB Check (Figure 4.2) was inconclusive, the odd and even light curves from the TESS Exo-MAST website (Figure 5.1) showed that there is very little chance of a near-eclipsing binary, the result of another star creating a change in light, because the transit depth is the same on both the even and odd light curves. Our Normalized Relative Flux Depth over Time for the Target Star (Figure 4.3) was also reasonable and there is little reason to suspect a NEB, although it still remains a possibility.

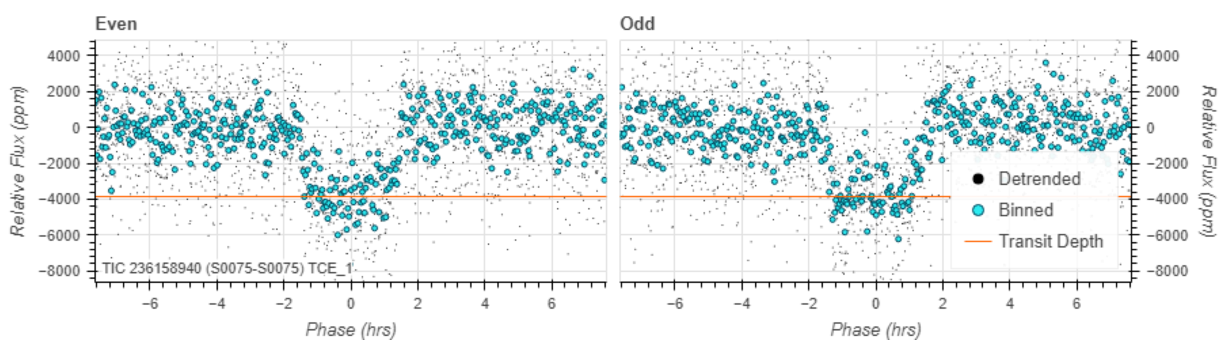


Figure 5.1: Even and Odd Light Curves

The chi^2 and FOV values from our AstroImageJ analysis showed a statistical significance with a p-value less than 0.0001, using a significance value of 0.05. Therefore, although there is a very small possibility of a false positive, we believe that TOI 5868.01 is an exoplanet.

5.2 Results Follow Up

Unfortunately, we were unable to find any comparison documents, so our data will still need to be reevaluated with additional data on another night. However, looking at the stellar and planetary parameters of TOI 5868.01, we conclude that if this is an exoplanet, it would most likely be a Hot Jupiter due to its size of 1.25 Jupiters and a shorter period of 2.68 days. Its star also has a very high effective temperature of 6,875.8 K and is 2.41 times the size of our sun, suggesting that it is a star that is much older than our own sun.

6. Conclusion and Future Work

We confirmed the presence of candidate exoplanet TOI 5868.01 to a significant degree. The resulting light curve extraction from the ground-based observation as well as the TESS data we collected and compiled appeared to prove its existence. However, we cannot reach a definitive conclusion on the validity of TOI 5868.01 as an exoplanet due to an inconclusive NEB check and analysis.

Future work will be required to validate TOI 5868.01 as an exoplanet. The NEB Analysis was inconclusive because we did not have a larger camera at our disposal and our data analysis was limited. In the future, we could perform radial velocity measurement using high-resolution spectrographs to help find more accurate mass and density, and also detect minute Doppler shifts caused by this planet orbiting its star. Additionally, using this method may help to rule out a false positive. This future work will further help to determine whether TOI 5868.01 is a valid exoplanet that may give us more insights into planetary systems and development.

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